(2)

QUARTERLY TECHNICAL REPORT #4
(1/1/93 - 3/31/93)

Sponsored by:
Advanced Research Projects Agency
Defense Sciences Office (DSO)
Vacuum Microelectronics Program
ARPA Order No. 8162/07 & /09 Program Code No. 2G10
Issued by ARPA/CMO under Contract # MDA972-92-C-0034

Contractor: Hughes Aircraft Company
Electron Dynamics Division
3100 W. Lomita Blvd.
Torrance, CA. 90509

Project Manager: Dr. David S. Komm
Tel #: (310) 517-5108
Fax #: (310) 517-5737

Title of Work:

RF VACUUM MICROELECTRONICS

1.0 Emitter Fabrication

1.1 Mask Design and Procurement

1.1.2 Mask Set #2

All layers of mask set # 2 were received prior to Feb. 1. A photograph of the overall reticle layout is shown in figure 1. There are 16 reticles per 1" wafer and 9 different chips per reticle for a total of 149 chips of which about 120 are expected to be usable (about 30 chips are too close to the wafer edge). On this mask set we concentrated on straightforward arrays of tips of different sizes oriented in such a way that they could be conveniently package onto TO-8 headers. In the previous experiments we found the most significant impediment to consistency in testing was the bonding, die-attach and packaging.

1.2 Process Optimization Experiments

1.2.1 Process #1.1

Testing of process lot 1.1 was completed in this quarter. An emission of 50μA (>99% to anode) was obtained from one array demonstrating continued improvement in the process. Failure modes of the tips were studied in more detail and a number of in-situ plasma cleaning and ambient gas tests were conducted.

The following general observations were made on the physical characteristics of the samples and the emission results from the first experiment (the first 7, in italics, are reprinted from the 2nd quarter report):

1) *Aperture diameters ranged from 3000 Å to about 2.0 μm.*

2) *Smallest apertures were obtained on the smallest pyramids and thus the pyramid tip tended to be well below the plane of the aperture.*

3) *Some large pyramids with large apertures had tips above the plane of the aperture.*

4) *There were no glaring trends relating emission current to geometry for the space of geometries studied in this experiment.*

5) *There seemed to be much more variation from sample to sample than there was on any particular sample. That is despite the fact that on a single header there were three devices with often very different geometries, their emission characteristics were not drastically different.*

6) *There was some scaling observed in emission current between the largest arrays (10,000 and 20,000 tips) and the "standard" arrays of 400 tips.*

7) *The choice of tip metal between Au and Pt did not have any apparent effect on the emission characteristics.*

8) SiO_2 appered to be far superior as an interlayer dielectric...all samples with SiO_2 showed some emission while no significant emission was observed from any of the samples using Si_3N_4 as the dielectric.

9) There was no apparent difference in the breakdown voltage of samples with 4000 Å dielectric and those with 6000 Å dielectric nor was there any difference in the leakage current.

10) Based on studies of emission in gas ambients, the leakage appears to be surface related rather than bulk leakage through the dielectric.

Please refer to the testing section for a more detailed discussion of the effect of various gasses on emission and leakage current.

We conducted a number of cross section studies to determine the actual geometries of the devices. One such cross section is shown in an figure 2 along with an anlgled view of a similar structure . The cross section studies provided definitive calibration on the dielectric thickness in the field and on the emitter tips as well as the shape and location of the boundary between the interlayer dielectric and the vacuum surrounding the emitter tips.

A series of dielectric etch experiments was also performed with the gate metal in-place as an etch mask. The gate metal was then removed and the shape of the etched dielectric was characterized in the SEM. Two photos of different etch times are attached in figure 3. Note that the shorter etch time results in only partial removal of the dielectric from around the emitter tip. These devices were subsequently tested to see if there was any effect on the leakage current or emission characteristics. No real difference in leakage was observed indicating that the dielectric etch does not represent a major factor in the variation of leakage current or emission.

After testing, devices were analyzed in the SEM to observe the specific failure modes. The most common failure mode involved single tip disruptions as shown in figure 4. Another observe failure mode is an anode arc only observed on a few samples also shown in figure 4. This is probably due to the release of a substantial amount of trapped gas and the formation of a discharge during operation. The single tip disruptions indicate that only a few tips are emitting at any given time and that only a dozen or so can be activated before one tip fails short.

1.2.2 Process #1.2

We developed a new technique to obtain thick dielectric without compromising the submicron apertures of the FEA in an off-line trial. The technique was described in detail in the previous quarterly report. A photo of the new emitter tips is shown in figure 5. Note that the tips protrude through a thick oxide and have the desirable "pencil" shape (sharp point on top of a narrow shaft) required for maximum field enhancement. A completed FETRODE using this technique is also shown in an attached photo. FETRODE 19 proved to be the most ideal of the samples in process lot #1.2. We obtained roughly the same turn-on voltage with a more robust structure and thus failure occurred at higher voltages and correspondingly higher emission currents.

FETRODE MASK: FT02

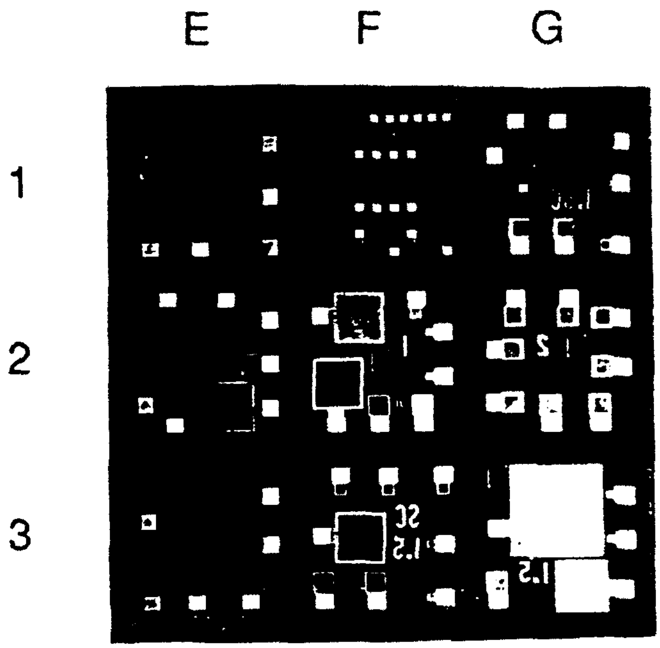

Figure 1

FETRODE mask set 2: The unit cell (field) consists of 9 chips. Chips are 2 mm square (the field is 6 mm square). The mask consists of array sizes from 9 to 40,000 tips at densities from one tip per 100 square microns to one tip per 4 square microns.

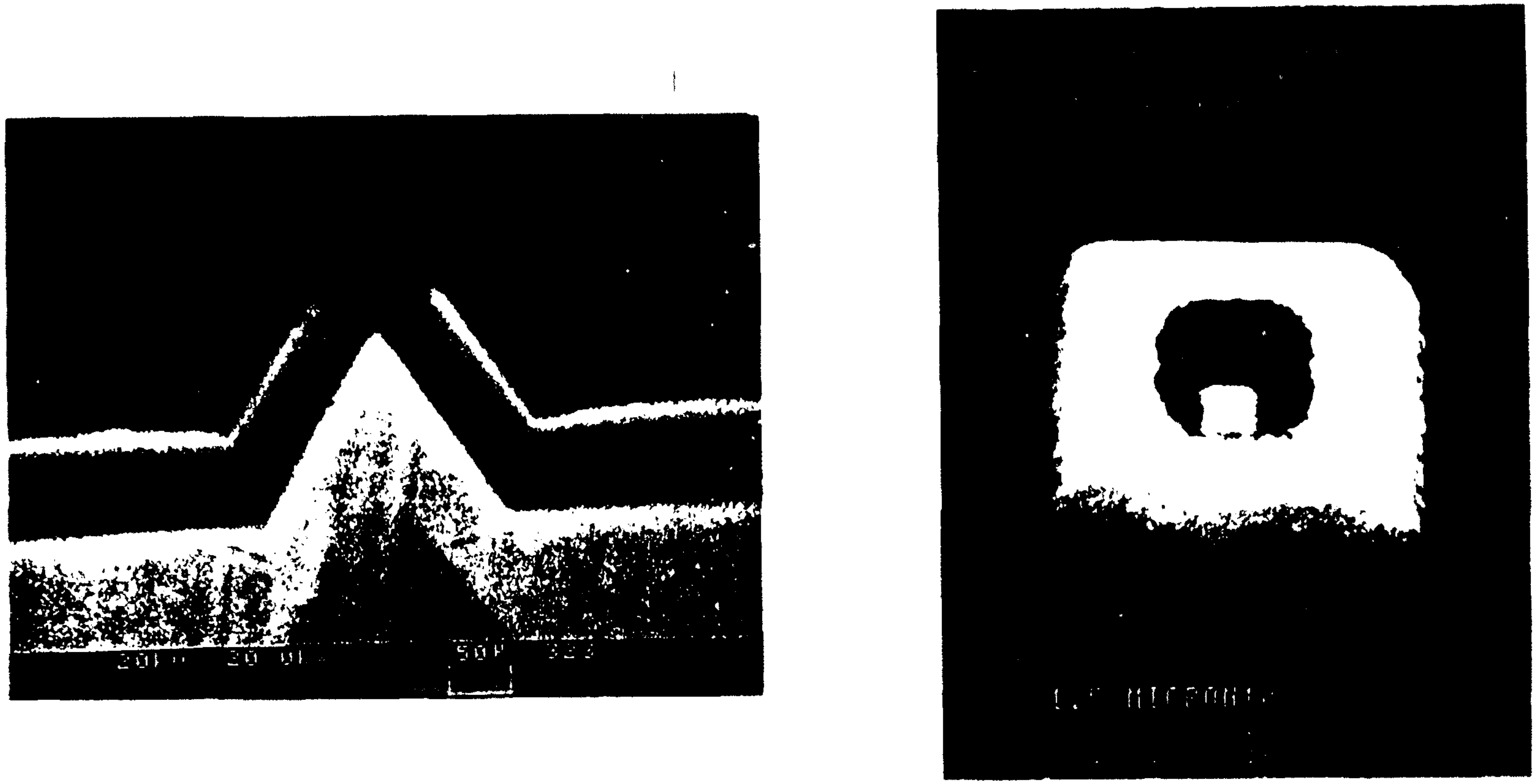

Figure 2

Cross section and low angle scanning electron micrograph of 1.5μm FETRODE from sample 13. Note that the dielectric thickness is slightly less on the sidewalls of the emitter... about 0.8x the thickness in the field.

Figure 3

Oxide etch experiment: The FETRODE chip on the right was etched for the nominal time of 30 sec. the one on the left (identical structure from the same wafer) was etched for an additional 1 minute. Both had the gate metal removed after the oxide etching. Both had the same metal gate aperture shown in figure 2.

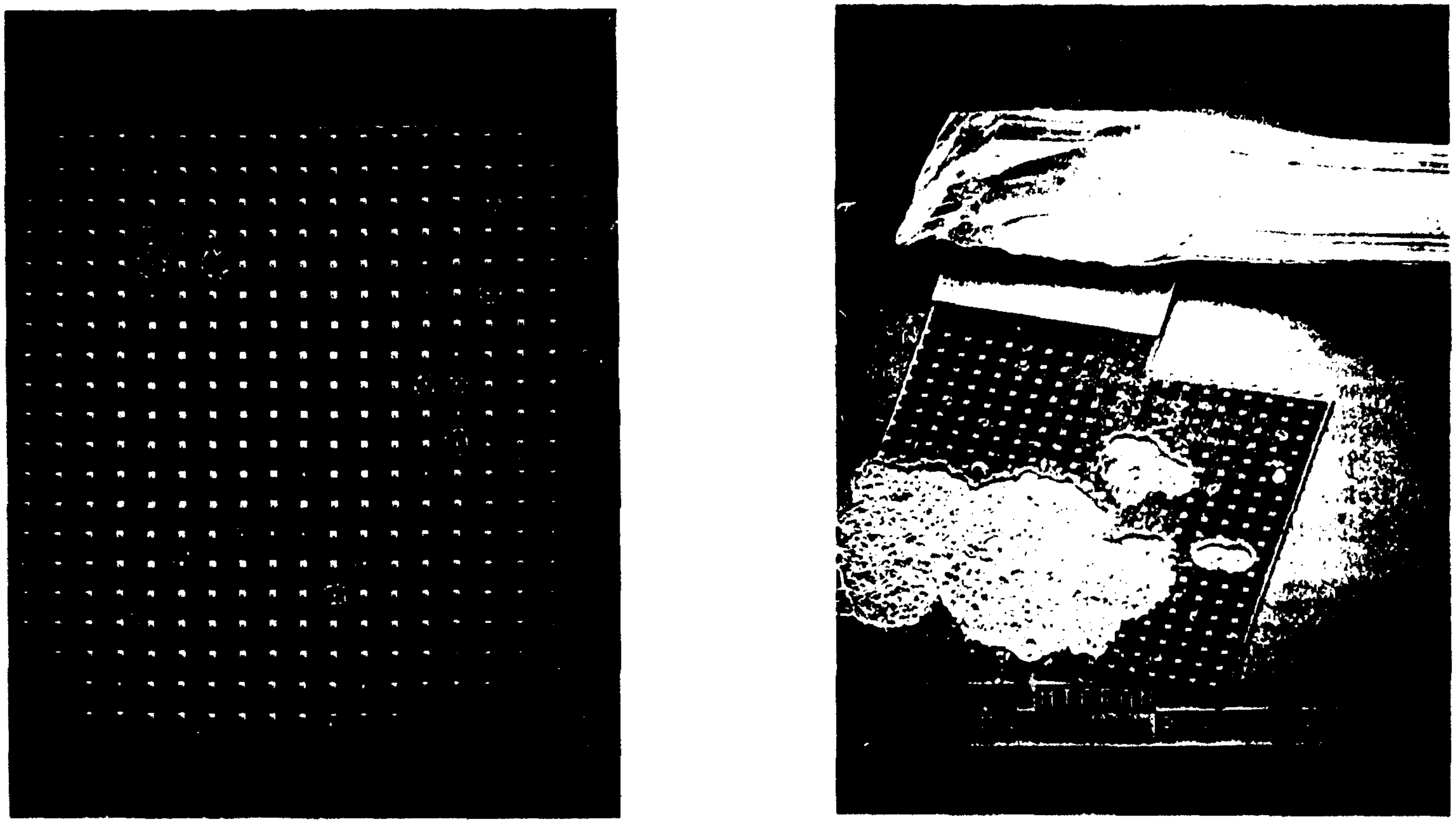

Figure 4

The two observed failure modes for Hughes FETRODES. The photo on the left shows the more common single point failures...there are rarely more than a dozen blown tips on any tested array. The photo on the right shows the less common failure mode (<5% of samples), obliteration of the gate metal, believed to be caused by a gate to anode discharge.

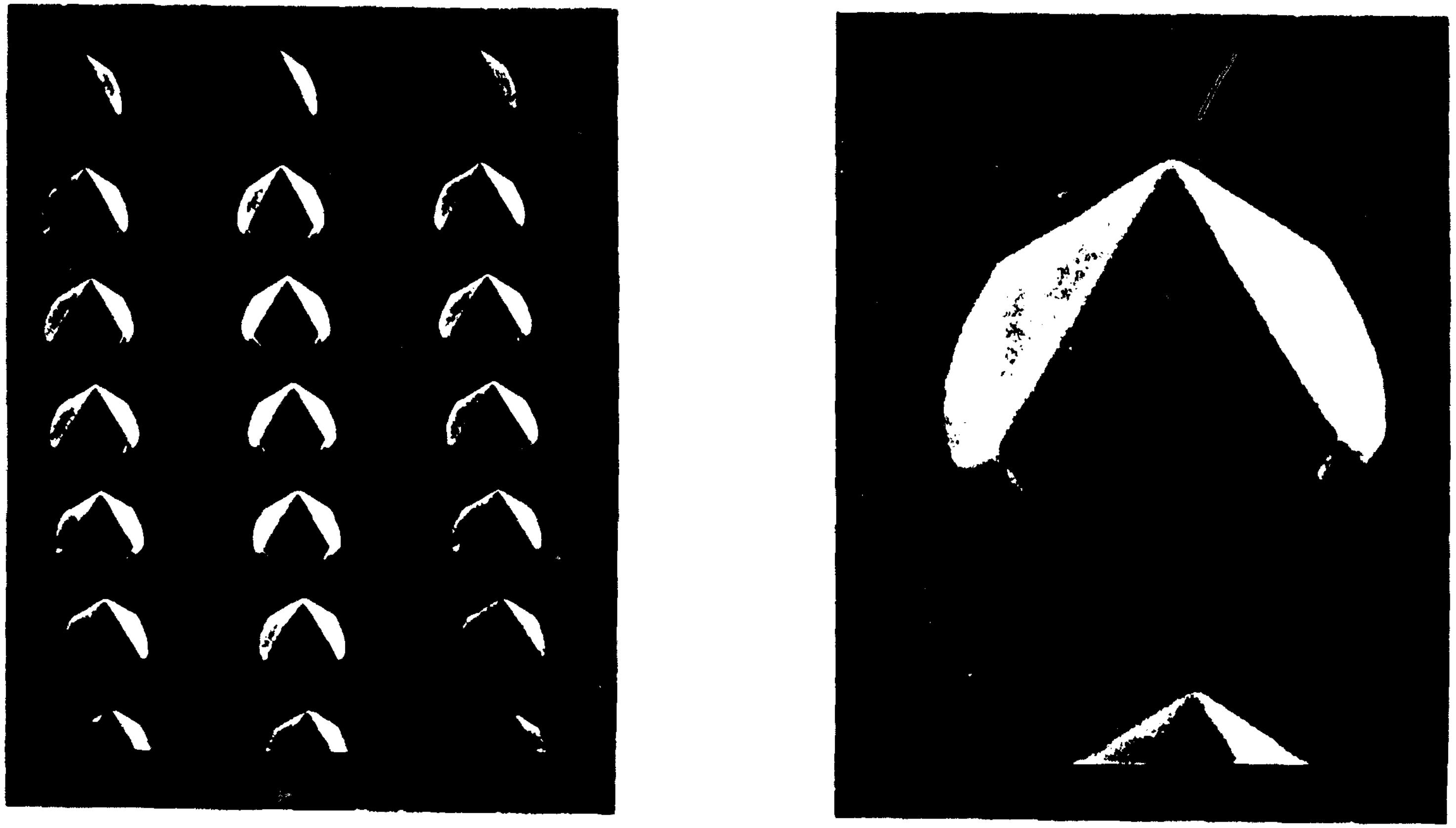

Figure 5

Emitter tips formed using modified 2-dielectric process. The tips protrude through a 0.5μm Si_3N_4. Subsequent processing adds another 0.6μm SiO_2 layer so that gate emitter dielectric is > 1μm thick.

2.0 Emission Testing

Emission testing continued in this quarter. Eleven devices were evaluated, and experiments with in situ processing were undertaken. In table I we list the devices that were evaluated and studied in this quarter. Details of each evaluation run can be obtained from the description column of the table I. Samples F12 are gold tips with 6kA of silicon nitride dielectric. Sample F14 are platinum tips with 6kA of silicon dioxide dielectric. The letters following the sample identification indicated the array size. Samples F19 and F22 are from the second process lots and all have thicker dielectrics, F22 also have larger gate openings.

A number of plasma cleaning processes continued to be investigated they include oxygen and hydrogen plasma cleaning. Oxygen plasma processing was used to lower the leakage current followed by a brief hydrogen plasma process to deoxidize the tips. This seemed reasonable and yielded only limited results.

In other attempts to affect the tip properties we tried introducing oxygen, hydrogen, and argon into the system while operating the devices. There were some interesting results but the repeatability was poor. The gas pressures at which an effect could be seen was very low, 1×10^{-8} to 1×10^{-7} torr. We hypothesis that the effect of the gas is occurring only above the active tips, where the emitted electrons from the tips excite the gas atoms creating positive ions which in turn interact with the active tips. The reason for these experiments were to determine if we could suppress active tips before they self-destructed thus allowing time for other tips in the array to become active. The results showed some effect but was not as promising as expected.

We performed several experiment designed to modify the work function of the tips during operation. This was accomplished by depositing various materials onto the device in the test chamber. A dispenser cathode was placed at the opposite end of the anode tube and barium and barium oxide was deposit onto the array during operation. The dispenser cathode was operated at various temperatures up to 1200 C. No effect on the emission of the device was observed. We also co-deposited barium and scandium, in a similar arrangement, in an attempt to synthesis on the emitter tips the low work function of a scandate cathode. This attempt was not successful.

SAMPLE		RUN #	DESCRIPTION OF RUN
F12-1	A2	1	Leakage 0.1 uA at -16 v No emission.
F12-1	L1	1	Leakage 0.1 uA at -10 v No emission.
F12-1	B2	1	Leakage 0.1 uA at -21 v No emission.
F12-1	C2	1	Leakage 0.1 uA at -10 v No emission.
F12-6	B3	1	Leakage 0.1 uA at -20 v No emission.
F12-6	C1	1	After #1; Failed at -64 v.
		2	After #1; leakage about 1 uA at -3 v.
F12-2	A2	1	Leakage 0.1 uA at -12 v No emission.
F12-5	B3	1	Leakage 0.1 uA at -13 v No emission.
F12-5	D3	1	Nothing' up to -164 v.
F14-8	B3	1	Leakage 0.1 uA at -55 v Emission 0.2 nA
F14-8	L2	1	possibly some emission but shorted at about 46 v.
F14-4	B2	1	Shorted from start
		2	Not shorted -112 v some emission.
F14-4	A2	1	Leakage 0.5 pA at -93.00 0.1 nA emission.
		2	After #1; .2 uA at -65 v, no emmision.
		3	After #1 and 18hr of Ba deposition with Ba source at 3 inches away and at 1150 Cbr; no observed change and device failed at -83 v.
F14-4	L1	1	Leakage 0.1 uA at -21 v No emission
		2	After #1; failed 25 v, no emission.
F14-4	C2	1	Leakage 0.1 uA at -60 v Emission 18 pA
		2	first run with Ba source on. This device was being run during the Ba and Sc deposition.
		3	second run with Ba source on
		4	third run with Ba source on
		5	forth run with Ba source on Not printed to -10 v only
		6	Fisrt run after Sc deposition and with Ba source on
		7	After #1 and 18hr of Ba deposition with Ba source at 3 inches away and at 1150 Cbr;leakage 2. uA at -90 v; about 1 nA of emission.
F14-15	B3	1	At 28 v, leakage 8 uA no emission
F14-15	L2	1	got to 105 v, leakage .5 uA no emission.
		2	got to 125 v, leakage .8 uA, bursts of emission.
		3	got to 188 v, leakage 2.0 uA, no emission.
F14-15	D3	1	got to 75 v, leakage 42. nA emission
F19-2	A1	1	Got to -76 v 0.6 uA and no noticeable emission
		2	Got to -92 v, 0.9 uA and 3 nA emission. Put on aging rack (Kevin's).
		3	Shorted
F19-2	D3	1	Got to -52 v, 150 nA leakage, no emission. Held for a while.
		2	Probably shorted at -87 v.
		3-1	Dead
F19-2	B3	1	Got to -87 v with w uA leakage and 11 nA emission.
		2	Last stable point was -97 v at 1.3 uA leakage and 88 nA emission. Then 38 uA leakage.
		3	Now about 2 M ohm
F19-1	D3	1	Shorted: Resistance << 1 M
F19-3	D3	1	-104V, 2.8 uA leakage; 19 nA emission
		2	Got to -96 v, 2 uA leakage, 8 nA emission
		3-1	Got to -97 v, 12 uA leakage, 22 uA emission
		4-1	Got to -26 v, 25 nA leakage, no emission. Found out that the e-g voltage was being calculated wrong by FET1.4.4. Corrected and re-compiled
		5-1	Got to -106 v, 13 uA leakage, 53 uA emission, then gate current increased to 24 uA and emission fell to 35 uA.
		6-1	Got to -99 v, 4.5 uA leakage, 16 uA emission, then abrupt drop in emission to 0.1 uA, but started to come back when Keithlys hung up
		7-1	Got to -100 v, 2.1 uA leakage, 15 uA emission, then abrupt drop in emission to 3 uA and increase in gate current to 7 uA. Ran device down.

		8-1	At -96 v 3 uA leakage, 1.2 uA emission
		9-1	Anode at +750 v. At -96 v 2.5 uA leakage, 1.4 uA emission
		10-1	Anode at +1000 v. At -96 v 2.3 uA leakage, 1.7 uA emission
		11-1	Anode at +300 v. At -96 v 1.9 uA leakage, 0.63 uA emission
		12-1	Anode at +625 v. At -96 v 2.1 uA leakage, 1.0 uA emission
		13-1	Anode at +400 v. At -96 v 2.8 uA leakage, 0.87 uA emission
		14-1	Anode at +875 v. At -96 V 2.3 uA leakage, 1.4 uA emission
		15-1	Anode at +500 v. At -96 v 2.6 uA leakage, 1.1 uA emission
F19-4	B2	1	-94 v, 1.5 uA leakage, .15 uA emission
		2	shorted.
F19-4	C2	1	Shorted
F19-5	L1	1	Never really got started
		2	Got to -62 v 3.6 uA leakage, 0.5 nA emission then shorted.
		3	Definitely shorted
F19-5	C2	1	Shorted: Resistance << 1 M
F19-6	B2	1	Got to -108 v, .43 uA leakage, .19 uA emission tried to quit, device apparently failed
		2	Definitely shorted
F19-6	C2	1	Shorted
F19-6	L1	1	Got to -38 v, 1.2 uA leakage, .14 nA emission reversed voltage and backed down
		2	Got to -39 v, 1.6 uA leakage, .17 nA emission; reversed voltage and backed down.
		3-1	Run with 100K resistors. Greatly enhanced leakage Ran up to -21 v 15 uA leakage, no emission
		4-1	Ran up to -66 v, 18 uA leakage, 9 uA emission suddenly failed.
		5-1	Dead

SAMPLE ID		DATE OF RUN	RUN #	DESCRIPTION OF RUN
F22-1	D3		1	0.2 uA leakage @ -34 v; no emission
			2	0.1 uA leakage at -32 v; no emission
			3	10.0uA leakage at -50.0v SMU -30vapp; trace emission
			4	3.8uA leakage at -41v; no emission
			5	21 uA leakage at -50v; possible trace emission
			6	60 uA leakage at -76v; 0.6uA emission
			7	Shorted at start
			8	Shorted at start
F22-1	C1		1	0.47 uA leakage @ -104 v; 33 nA emission
			2	Shorted at start
			3	Shorted at start
F22-1	B3		1	0.1 uA leakage @ -35 v; no emission
			2	Shorted at start
			3	Shorted at start
F22-2	D3		1	0.1 uA leakage @ -35 v; no emission
			2	10uA leakage at -42v; trace emission
			3	10uA leakage at -48v; trace emission
			4	Shorted at start
F22-2	C1		1	Was 21 nA leakage @ -77 v; no emission; then was 17 uA leakage @ -75 v; no emission. Possibly failed
			2	Shorted at start
			3	Shorted at start
F22-2	B3		1	Shorted at start
			2	Confirmed
			3	Shorted at start
			4	Shorted at start
F22-3	D3		1	0.1 uA at 33 v no emission
			2	10uA leakage at -44v; trace emission
			3	Shorted at start
F22-3	C1		1	Shorted at start
			2	Shorted at start
			3	Shorted at start
F22-3	B3		1	0.1 uA at 34 v; no emission
			2	10uA leakage at -53v; 2.8nA emission
			3	10uA leakage at -16v; no emission
			4	Shorted at start
F22-4	L1		1	Pad lifted no currents to 200 v
F22-4	A2		1	0.1 uA at 30 v no emission
			2	10uA leakage at -49v; trace emission
			3	10.0 uA at -52 v trace emission (H2 experiment) shorted
F22-4	B2		1	0.1 uA at 32 v no emission
			2	10uA leakage at -61v; 0.3nA emission
			3	15uA leakage at -63v; 0.05nA emission
			4	Shorted at start
			5	Shorted at start
F22-4	C2		1	0.1 uA at 31 v no emission
			2	10.0uA leakage at -34v; no emission
			3	Shorted at start
F22-5	B2		1	Shorted at start
			2	Shorted at start
F22-5	C2		1	Shorted at start
			2	Shorted at start

F22-5	L1	1	0.1 uA at 15 v no emission
		2	10.0uA leakage at -18v; no emission
		3	Shorted at start
F22-5	A2	1	0.1 at 34 v no emission
		2	10.0uA leakage at -45v; no emission
		3	Shorted at start
F22-6	B2	1	Shorted at start
		2	4.0uA leakage at -62v; 0.2uA emission Shorted
F22-6	L1	1	Pad lifted no currents to 200 v
F22-6	A2	1	0.1 uA at 36 v no emission
		2	5.0uA leakage at -57v; 0.1nA emission
		3	Shorted at start
F22-6	C2	1	0.1 uA at 28 v no emission
		2	10.0uA leakage at -35v; trace emission
		3	Shorted at start
F19-12	A1	1	.1 uA leakage at -28 v. No emission. May have short.
		2	.1 uA leakage at -5 v. Device damaged.
F19-12	B3	1	Starts emitting at -35 v. Went up to -51 v and have 20 nA Ie, 10 nA Ig, 10 nA Ia. Stopped test.
		2	Leakage 0.1 uA at -11 v no emission.
F19-12	D3	1	.1 uA leakage while holding at -72 v,.5 nA emission.
		2	After aging on aging rack. No activity at all up to -200 v
F19-12	L2*	1	Shorted from start.
F19-13	A1	1	Leads misconnected.
		2	0.1 uA leakage at -56 v. No emission.
F19-13	B3*	1	Pad lifted. Up to -80 v, no emission or leakage.
F19-13	D3	1	0.1 uA leakage at -39 v. No emission.
F19-13	L2	1	0.1 uA leakage at -28 v. No emission.
F19-15	A2*	1	0.1 uA leakage at -142 v. May have shorted.
		2	0.1 uA leakage at -11 v. Device damaged.
F19-15	B2*	1	Started emitting at -50 v. 0.1 uA leakage at -72 v.
F19-15	C2	1	.1 uA leakage at -62 v. Trace emission. Emission started at -52 v.
		2	After aging on aging rack. No activity at all up to -200 v
F19-15	L1*	1	Up to -128 v. No leakage or emission.
F19-16	A2*	1	Started to emit at about -55 v. May have shorted at -59 v.
		2	0.1 uA leakage at -53 v. No emission. Much more leakage than first measurement.
F19-16	B2	1	Shorted from start.
F19-16	C2	1	0.1 uA leakage at -44 v. No emission.
F19-16	L1*	1	Tested to -106 v. No leakage or emission.
F19-17	A2*	1	0.1 uA at -46 v. No emission.
F19-17	B2*	1	Tested to -108 v. No leakage or emission.
F19-17	C2	1	0.1 uA leakage at -50 v. Some emission.
		2	Tested to -46 v. No emission. Stopped test.
		3	0.1 uA leakage while holding at -54 v. Trace of emission.
		4	Leakage 0.5 uA at -95V. Emission peaked at 0.4 uA then decreased with the introduction of O2 to about 5e-7 torr.
		5	Rerun, No O2 to -97V. Results about the same. The same level of emission increased about 10V.

		6	emission 96% and 2uA with 2.5e-6 torr O2
		7	smaller leakage then last run but lower emission.
		8	rerun at 1.0e-5 torr O2. Leakage lower then last run emission not as high as last run.
F19-17	L1*	1	Tested to -200 v. No emission or leakage.